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Effectiveness of constructed farm wetlands in attenuating faecal indicator fluxes to watercourses from yard runoff on livestock farms

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Abstract

Constructed farms wetlands (CFWs) are increasingly being used to treat faecally contaminated 'dirty waters' from yard areas on livestock farms. The findings of the present study, undertaken at the Pwllpeiran experimental CFW, West Wales, provide empirical data on the effectiveness of CFWs in attenuating faecal indicator organism (FIO) concentrations and fluxes to the receiving waters to which they discharge; and insight into the extent to which attenuation rates are affected by retention times within the CFW and seasonal factors. Based on the maximum flows that a CFW is being designed to treat, an equation is developed to enable estimates to be made of the size of wetland required to achieve a desired level of FIO attenuation. Other aspects of CFW design to optimise FIO attenuation are considered, including the construction of frequent baffles (transverse ridges), leaving parts of cells unvegetated and incorporating an initial settling pond.

KEYWORDS
bacteriological, catchment management, constructed wetland design, pollution, remediation, water quality

1 | INTRODUCTION

Faecally contaminated 'dirty waters' generated in yard areas on livestock farms, typically derived from a combination of natural runoff from yards during wet weather and the washing of yards, milking parlours and so on, represent a significant source of faecal indicator organisms (FIOs) within catchments, which may potentially impact coastal waters. Article 11 of the Water Framework Directive [Council of the European Communities (CEC) 2000] requires that a 'programme of measures' be adopted to ensure compliance of designated bathing and shellfish waters with water quality standards. The FIO-based microbial standards have become more stringent since 2015 following implementation of the 2006 Bathing Water Directive (CEC, 2006). Defra's *Mitigation Methods: User Guide* (Newell Price et al. 2011) identifies a wide range of potential interventions for addressing agriculture-derived pollutants in catchments draining to 'protected' areas, which include bathing and shellfish growing waters. Unfortunately, the empirical evidence-base defining the effectiveness of interventions to control FIOs is very limited compared with nutrients, biochemical oxygen demand (BOD), chemical oxygen demand (COD) and suspended sediments (SSs), and the design of individual measures is often based on 'expert judgement'. There is, therefore, an operational and policy need to identify the most effective measures that might be adopted to mitigate FIO losses to watercourses from livestock sources.

Although dirty waters from farmyards may be intercepted and stored for subsequent disposal to land, storage of large volumes of dirty water can be costly and present additional pollution risks. Increasing attention is therefore being given to on-farm treatment, particularly to measures that rely on natural and sustainable pollutant attenuation processes, most notably constructed farm wetlands (CFWs). The majority of CFWs, as in the present study, are of the 'free water surface' (FWS) type. These typically comprise 'one or more shallow, free surface flow constructed cells containing emergent vegetation …' which are '… designed to receive and treat lightly contaminated surface water runoff from farmyards, in such a manner that any discharge from the wetland will not pollute the water environment' (Carty et al., 2008, p. 12).

Over recent years, several systematic reviews and guidance documents have been published on CFWs, notably: Avery (2012); Department of the Environment, Heritage and Local Government, Ireland (2010); Mackenzie and McIlwraith (2015) and Newman et al. (2015). Whereas the latter report demonstrates the potential effectiveness of wetlands in mitigating various pollutant loadings to downstream receiving waters, no data are presented on FIOs. The present study, undertaken at the Agricultural Development and Advisory Service (ADAS) experimental CFW at Pwllpeiran in West Wales, UK, investigated rates of attenuation of the two standard EU bathing water FIO parameters at the time [presumptive *Escherichia coli* ('pEC') and presumptive intestinal enterococci ('pIE')] and some of the factors controlling these. The results not only enable evidence-based assessments to be made of potential benefits of CFWs in reducing FIO fluxes to receiving waters but also help inform design, construction and operational guidelines for CFWs in relation to FIOs.

2 | MATERIALS AND METHODS

2.1 | The Pwllpeiran experimental CFW and its setting

The FWS CFW was designed and professionally constructed for experimental purposes to a design informed by the Anne Valley integrated constructed wetlands, Ireland, which accorded closely with the specifications in *CFW Design Manual for Scotland and Northern Ireland* (Carty et al. 2008). It is located on a gently sloping, SE-facing valley side, at an altitude of 220–241 m above sea level, with poor-quality grassland that had not been improved or intensively grazed for many years. The CFW comprises a linear cascade of five elongated, shallow, vegetation-emergent wetland cells (Cells 1–5) with areas of 358, 331, 696, 882 and 533 m^2, respectively (Figure 1). The cells were lined with locally sourced clay and compacted with minimise seepage losses. The CFW is isolated from farmyard runoff and other significant point sources of pollution in order to control pollutant inputs. Flow was artificially maintained during the experimental studies by pumping water from the nearby stream, Nant Peiran, into Cell 1. A containment pond, lined with a geo-membrane, was constructed below the outlet of the lowest cell to ensure that effluent waters could, if necessary, be prevented from discharging to the stream.

The cells were constructed with 1.5-m freeboard and baffles (transverse ridges) to minimise streaming of flow, with each having a maximum water depth of 300 mm. The clay base was covered with topsoil and planted at a density of two plants per square metre with single transverse bands of three to five of the following species in each cell: *Caltha palustris* (marsh marigold), *Carex riparia* (greater pond sedge), *Glyceria maxima* (reed sweetgrass), *Iris pseudacorus* (yellow flag), *Juncus effusus* (soft rush), *Phalaris arundinacea* (reed canary grass) and *Typha angustifolia* (lesser reedmace).

2.2 | Experimental design

Seven experimental runs were conducted over the period June 2007 to February 2012: Runs 1, 2 and 4 between 28 June and 2 October—that is, during or within 2 days of the end of the summer bathing season (here regarded as 'summer' runs); and Runs 3, 5, 6 and 7 between 26 October and 5 February ('winter' runs). Once flow ('maintenance flow') was established through the CFW, measured quantities of a microbial tracer (MS2 coliphage) and 'slurry' (a variable mixture of beef cattle slurry, farmyard manure and yard runoff) were added. Addition of slurry (over a period of *c*. 1 h) led to a brief increase in flow rate, which replicates the impact of rainfall-induced episodic inputs of dirty water from yard areas. MS2 coliphage, a virus that infects the *E. coli* host bacterium, is an effective means of determining retention times (RTs) in constructed wetlands (Hodgson et al. 2003). It is usually absent, or present in very low concentrations, in the natural environment. Water flow and fluxes of FIOs in the maintenance flow at the inlet to the wetland (sampling point W0) and of tracer and FIOs at the outlet of each cell (points W1–W5) were monitored during each run.

In the present analysis, it is assumed that inputs of water to the CFW from surface runoff, natural soil throughflow, flow from any pre-existing land drains located upslope and direct rainfall, and losses through evaporation/evapotranspiration, are negligible compared with the average inputs of 0.83–2.70 L/s in maintenance flow during the experimental runs. Unfortunately, during Runs 1 and 2, very marked reductions in flow were recorded through the final two cells, especially Cell 4 in which flow fell by over 85%. Because there were no breaches in the cell banks, substantial leakage was clearly occurring through the beds of the cells. In what proved to be successful repair work undertaken on these two cells in October 2009, it was found that some of the leakage, if not most, was occurring via pre-existing land drains.

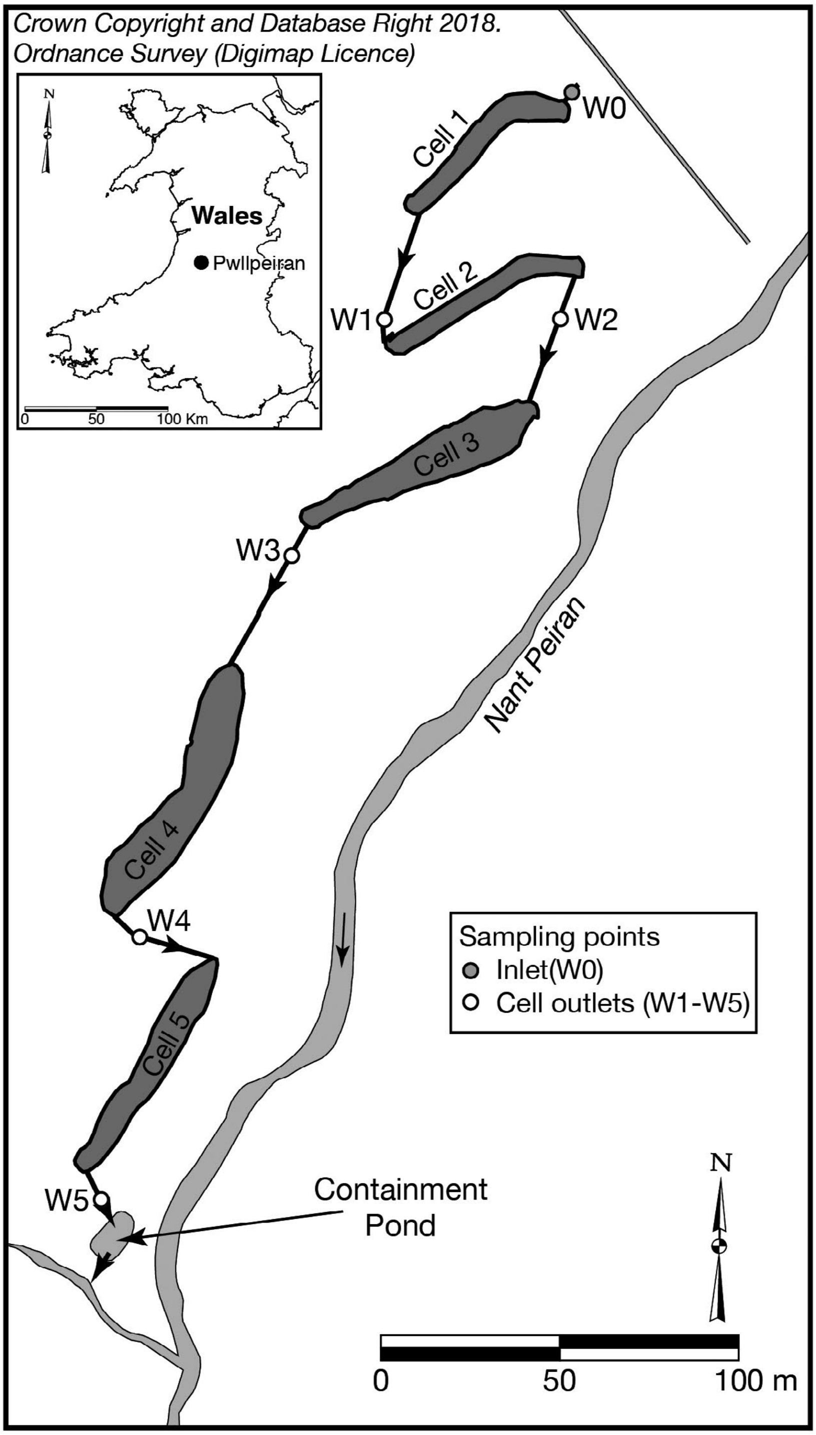

FIGURE 1 Location of the experimental constructed farm wetlands

2.3 | Field methods

Flow at points W0–W5 was measured using a plastic chamber with a 90° v-notch weir plate designed to record flows in the range 0–20 L/s. Four recording pressure transducers (Van Essen instruments Divers®) were fixed inside each box, two submerged and two to record atmospheric pressure to enable compensations to be made for changes in ambient air pressure. Water sampling at W0–W5 was undertaken using ISCO 3700 autosamplers: at intervals of 1 h during the first 48 h of each study and thereafter at 4 h intervals through to 120 h, by which time the pollutant flux had effectively passed through. Samples were taken using presterilised pots.

2.4 | Laboratory methods

All microbial analyses were completed within 24 h of collection. pEC and pIE were analysed using membrane filtration following the methods and reagents as specified in Environment Agency (EA) (2000) and are reported as colony forming units (cfu)/100 ml.

MS2 coliphage enumeration used the double agar overlay method (EA, 2000; Havelaar & Hogenboom, 1984), with results reported as plaque forming units (pfu)/ml.

2.5 | Determination of hydraulic retention and breakthrough times

Because the cells of the Pwllpeiran CFW, as is typical of CFWs in the United Kingdom, are somewhat irregular in shape and depth, their capacity is difficult to define accurately. Flow through such wetlands is also extremely variable, being driven by rainfall and regular washings from yard areas and so on, and preferential flow paths often develop. In these circumstances, the classic hydraulic retention time (HRT) equation (typically expressed as: reactor volume/volumetric flow rate) is of limited value in characterising the time available for 'processing' (in this case for FIO attenuation) in CFWs. Therefore, in the present study, the cumulative 15-min fluxes of the MS2 coliphage tracer at the cell outlets have been used for this purpose. Attention focuses upon the time taken (RT) for 50% of the total water flux to pass through (here referred to as 'RT-50'), which provides a measure of the average time that water spends in individual cells or the CFW as a whole. In addition, HRTs have been calculated from cell volume and flow estimates in order to compare these with the empirically derived RT-50 values—thus providing insight into the preferential streaming of flow, which will reduce the empirically measured RT-50 below that of theoretical HRT. Also, from inspection of the MS2 coliphage concentrations at the cell outlets, sharp increases could be detected when tracer started to pass through to the next cell down the cascade (here referred to as 'breakthrough time').

2.6 | Estimation of FIO inputs

Inputs during the experimental runs are derived from three sources:

2.6.1 | Injected 'slurry'

The volumes of slurry added and the mean concentrations pEC and pIE that they contained are presented in Table 2. The total inputs of pEC and pIE, which ranged from 3.4×10^8–2.5×10^{11} to 2.1×10^9–2.6×10^{11} cfu, respectively, likely reflect the wide variability in the FIO concentrations and fluxes encountered in dirty water runoff from farmyards.

2.6.2 | Maintenance flow

Flow at the inlet (W0) was monitored at 15-min intervals, and regular determinations (interpolated to 15-min) were made of pEC and pIE concentrations, thus enabling flux estimates to be made of FIOs entering the CFW from 1 to 120 h, that is, until after the flush of FIOs from the slurry had passed through. The inputs in maintenance flow over this period were of similar magnitude to those in the injected slurry, with pEC and pIE inputs ranging from 2.3×10^8–1.8×10^{11} to 7.6×10^7–1.8×10^{11} cfu, respectively.

2.6.3 | Other miscellaneous inputs

Although bunds prevented surface runoff entering the cells, other potential FIO sources include: throughflow from adjacent slopes; flow via pre-existing field drains (as far as possible these were sealed during construction) and direct faecal inputs to the cells from wildlife and livestock. FIO concentrations in any throughflow and drainflow are likely to be relatively low, particularly in view of the very low intensity grazing of the adjacent fields. Although inputs from wildlife, especially birds, may be significant in some wetlands, no waterfowl or seagulls were observed in the cells during any of the experimental runs; and none of the small numbers of sheep, which were occasionally present, were observed to enter the cells. Although these sources were not quantified, it has been assumed that their contributions will be small compared with the very large monitored inputs in the slurry and maintenance flow during the experimental runs. FIO inputs have therefore been estimated as the sum of the inputs in slurry and maintenance flow.

2.7 | Estimation of attenuation of FIOs through the CFW

The flow records and extrapolation of data from the analysis of the regular water samples taken from W1 to W5 allow estimates to be made of 15-min fluxes of the tracer and FIOs from the time of the initial input of tracer and slurry to the end of the monitoring period. Examination of pEC and pIE concentration plots revealed that, in each run, the concentrations at W1–W5 had returned to background levels by 116 h. This period was therefore used for the assessment of pEC and pIE attenuation. In order to take into account of water and FIO losses through leakage, estimates of attenuation have been derived from the mean discharge-weighted concentrations of FIOs at points W0–W5, calculated by dividing the total flux by the total volume of flow at each monitoring point. It should be noted that this provides a conservative estimate, because it does not take into account water losses though evaporation and evapotranspiration, which will effectively increase the concentrations present. These data have been used to derive estimates of attenuation, expressed as $\log_{10}$ reductions, both for individual cells and for the CFW as a whole.

3 | RESULTS

3.1 | Breakthrough and HRTs

MS2 coliphage concentrations displayed progressively smaller and lagged peak concentrations down the CFW cascade. The mean breakthrough time increases from 0.87 (Cell 1 outlet) to 22.5 h (Cell

5 outlet) and the mean RT-50 from 3.85 to 32.2 h (Table 1). Figure 2 reveals a strong linear relationship between the mean RT-50 at each cell outlet and the cumulative upstream cell area. Because the depth of water in each cell was maintained at 300 mm during the experimental runs, a similar relationship applies to upstream cell volume. The mean empirically derived RT-50 values are *c*. three to five times less than the traditionally calculated HRTs (Table 1). These differences are presumed largely attributable to the development of preferential, higher velocity, flow paths through the cells between 'dead zones' of relatively stagnant water. Such flow paths are likely to be particularly active at times when pulses of dirty water enter a CFW in response to episodic runoff from yard areas, a situation which was replicated in the present study by the brief increase in flow as the slurry was added to the background maintenance flow at the CFW inlet.

3.2 | Flow-weighted mean FIO concentrations in effluent waters

The flow-weighted mean concentrations of pEC and pIE recorded at the outlet of the CFW (i.e., at W5) over the five experimental runs undertaken after repair of the leakages ranged from 2.4×10^1–6.2×10^2 to 1.3×10^1–5.0×10^2 cfu/100 ml, respectively (Table 2). These figures provide an indication of the potential impact that the effluent waters would have upon a receiving water. They compare, for example, with GM pEC and pIE concentrations of 5.7×10^4 and 1.0×10^4 cfu/100 ml, respectively, recorded under high flow conditions in streams/rivers draining 15 rural catchments dominated by intensive livestock farming (≥75% improved pasture) in the United Kingdom during the summer bathing season (Kay et al. 2008). At times of high flow, which are critical in terms of the mobilisation and transport of FIOs within catchments, CFW effluent concentrations of the magnitudes recorded in these experimental runs are mostly at least 2.0 $\log_{10}$ lower than in streams draining such catchments. The effluent fluxes will therefore not adversely impact upon the microbial quality of streams or the coastal waters to which they ultimately discharge.

3.3 | Variations in FIO concentrations down the CFW

The GM discharge-weighted pEC and pIE concentrations recorded over the seven runs are presented in Figure 3. Despite the wide variability in the data recorded at individual sampling points, there is a clear, progressive reduction in GM concentrations down through the CFW, with GM pEC concentrations (Figure 3a) falling from 1.2×10^4 cfu/100 ml in the input waters (W0) to 1.9×10^2 cfu/100 ml at the outlet (W5), and pIE from 6.8×10^3 to 1.3×10^2 cfu/100 ml (Figure 3b).

3.4 | FIO attenuation and controlling factors

The amounts of pEC and pIE attenuation recorded cumulatively down through the CFW are presented in Table 3. The critical time in terms of increased FIO loadings to CFWs on UK livestock farms is typically from late October to the end of April when cattle are mostly housed indoors, conditions are generally wetter and the pressure on slurry/dirty water storage is greatest—that is, outside the summer bathing season, but potentially impacting upon shellfish waters. The four winter runs (which cover this period) had overall attenuations through the CFW ranging from 1.318 to 2.068 $\log_{10}$ (mean, 1.660 $\log_{10}$) for pEC and from 1.479 to 1.749 $\log_{10}$ (mean, 1.626 $\log_{10}$) for pIE. Complete data are only available for one summer run, which gave pEC and pIE attenuations of 1.919 and 2.048 $\log_{10}$, respectively.

Conventional regression analysis, including the constant or intercept (here termed 'RIC'), reveals very strong, statistically significant ($p < 0.001$), linear relationships between the cumulative $\log_{10}$ FIO attenuation recorded at the cell outlets and RT-50 (Figure 4), with the constants for both pEC and pIE not being significantly different from zero ($p > 0.05$). Because there can be no attenuation when RT-50 is zero, regression lines through the origin ('RTO') have also been calculated (Figure 4). These give rates of pEC and pIE attenuation of 0.0579 and 0.0566 $\log_{10}$/h, respectively, which are almost identical. What is also interesting from the plots is that the summer data,

TABLE 1 Pwllpeiran constructed farms wetlands (CFW): cumulative area and water volume, and mean breakthrough and retention times for the individual cell outlets

Cell outlet	Cumulative cell area (m^2) above outlet	Cumulative water volume (m^3) above outlet	HRT[a] (h)	Breakthrough time[b] (h)	RT-50[c] (h)
1	358	107	19.6	0.87	3.85
2	689	206	38.0	3.48	11.6
3	1385	415	74.7	6.84	16.9
4	2267	680	130	16.5	25.1
5	2800	840	162	22.5	32.2

Abbreviation: HRT, hydraulic retention time.

[a]HRT based on volume of water in CFW upstream of cell outlet/average water flow at outlet.

[b]Breakthrough = time taken for the first clear evidence of a significant increase in tracer flux at the cell outlet.

[c]RT-50 = time taken for 50% of the total MS2 coliphage tracer flux recorded at cell outlet to leave the cell.

though displaying a wider scatter, have a very similar distribution to the winter data. Thus, when (as here) allowance is made for differences in RT-50 between the various runs, the summer and winter attenuation rates are similar. It would seem therefore that the higher levels of incident UV light and warmer waters that favour attenuation during the summer are countered by other factors, the most likely being the shade afforded by the more substantial vegetation cover present at this time of year.

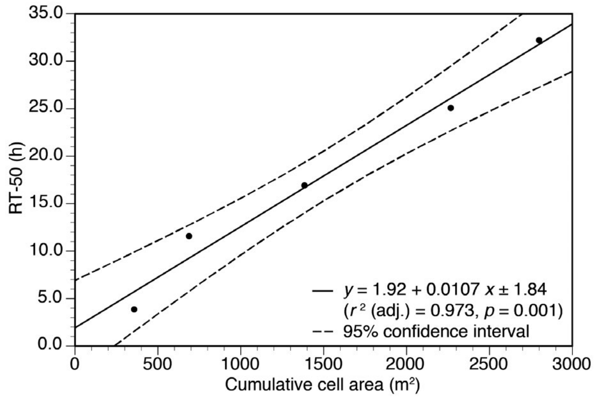

FIGURE 2 The linear relationship between the mean RT-50 at each cell outlet and the cumulative upstream cell area

4 | DISCUSSION

4.1 | Comparison with FIO attenuation data reported for existing operational FWS CFWs on livestock farms

As noted above, relatively few FIO studies have been undertaken of CFWs. We are only aware of seven previous investigations in the United Kingdom and Ireland (as detailed in footnote of Table 4) that have generated attenuation data for FWS CFWs. These provide 20 sets of attenuation figures for either presumptive or confirmed (here termed 'p/c') EC and 15 for p/cIE. The summary data presented in

TABLE 2 Details of slurry input at W0 during each experimental run and flow-weighted faecal indicator organism (FIO) concentrations recorded at outlet of final wetland cell (W5)

	Slurry input			Flow-weighted concentration at W5	
Run	Volume (l)	Mean pEC (cfu/100 ml)	Mean pIE (cfu/100 ml)	pEC (cfu/100 ml)	pIE (cfu/100 ml)
1	4590	8.3×10^5	4.8×10^5	Leakage	Leakage
2	4550	1.3×10^6	2.1×10^5	Leakage	Leakage
3	4530	1.9×10^6	5.7×10^6	5.9×10^2	5.0×10^2
4	3440	2.9×10^6	4.4×10^5	2.7×10^2	3.3×10^1
5	1370	4.1×10^5	1.5×10^5	2.4×10^1	1.3×10^1
6	2100	1.6×10^4	8.8×10^5	1.0×10^2	3.9×10^2
7	1000	2.5×10^7	3.5×10^6	6.2×10^2	3.7×10^2

Abbreviations: pEC, presumptive *Escherichia coli*; pIE, presumptive intestinal enterococci.

TABLE 3 Cumulative attenuation ($\log_{10}$) of faecal indicator organisms (FIOs) measured at the outlets of Cells 1–5 (W1–W5) during each sampling run[a]

	Run 1[b]	Run 2[b]	Run 3	Run 4	Run 5	Run 6	Run 7
Point	Summer	Summer	Winter	Summer	Winter	Winter	Winter
(a) Presumptive *Escherichia coli*							
W1	0.330	0.304	0.451	−0.288	0.521	−0.165	No data[c]
W2	0.499	0.805	0.584	0.031	0.397	0.221	1.072
W3	1.768	1.849	0.697	0.606	1.407	0.610	1.278
W4	Leakage	Leakage	1.351	2.067	1.930	1.023	1.739
W5	Leakage	Leakage	1.318	1.919	1.790	1.465	2.068
(b) Presumptive intestinal enterococci							
W1	0.939	0.316	0.283	−0.104	0.013	0.193	No data[c]
W2	1.277	0.718	0.155	0.318	0.753	0.272	1.136
W3	2.106	1.727	0.536	0.855	1.319	0.499	1.293
W4	Leakage	Leakage	1.490	1.724	1.249	1.068	1.476
W5	Leakage	Leakage	1.749	2.048	1.619	1.656	1.479

[a]Negative values indicate an increase in concentration (i.e., no attenuation).

[b]Significant leakage from Cells 4 and 5 during these runs.

[c]Failure of flow recorders.

Table 4 highlight the very wide variability in their effectiveness, with attenuation figures ranging from 0.000 to 4.505 $\log_{10}$ and 0.000 to 4.000 $\log_{10}$ for p/cEC and p/cIE, respectively. This inevitably reflects differences in a range of factors, including size, seasonality and access by livestock and wildlife, including wildfowl, though the relative importance of these and other factors cannot be established with any certainty from these limited datasets. The interquartile ranges for p/cEC and p/cIE attenuation are 1.191–2.693 $\log_{10}$ and 0.922–2.001 $\log_{10}$, respectively. The figures recorded in Runs 3–7 (for which complete data are available) of the present study range from 1.318 to 2.068 $\log_{10}$ for pEC and from 1.479 to 2.048 $\log_{10}$ for pIE, are, with one exception, within the interquartile range recorded in these previous studies. Thus, although the Pwllpeiran CFW was set up purely for experimental purposes, with the 'dirty water' inputs being artificially created and flow artificially maintained, the degree of FIO attenuation achieved is broadly consistent with FWS CFWs elsewhere. The present findings may therefore be applied with some confidence in informing the design and maintenance of FWS CFWs.

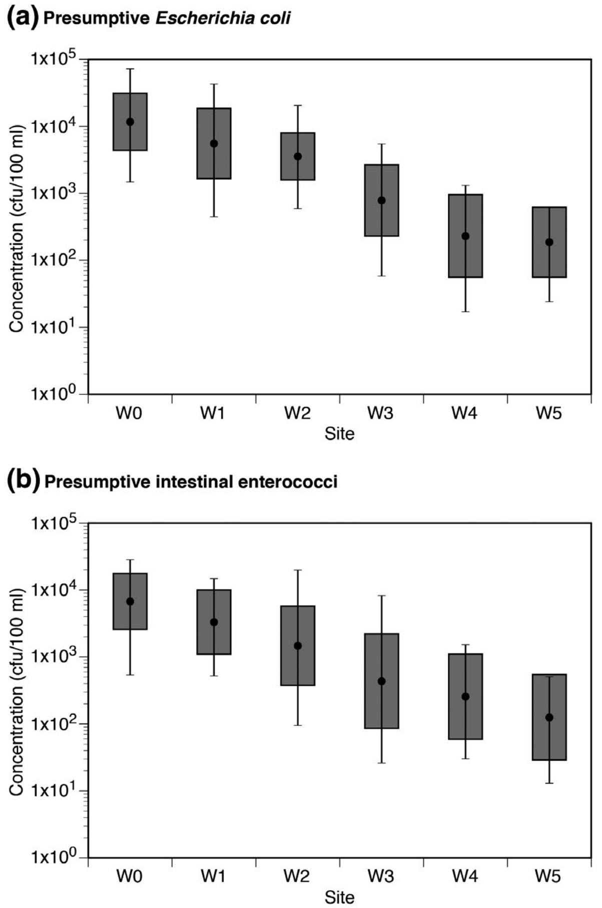

FIGURE 3 The GM discharge-weighted pEC and pIE concentrations recorded over the seven runs. Note the reduction in GM concentrations down through the CFW, with GM pEC concentrations (a) falling from 1.2×10^4 cfu 100 ml 1 in the input waters (W0) to 1.9×10^2 cfu/100 ml at the outlet (W5), and pIE from 6.8 × 103 to 1.3×10^2 cfu/100 ml (b)

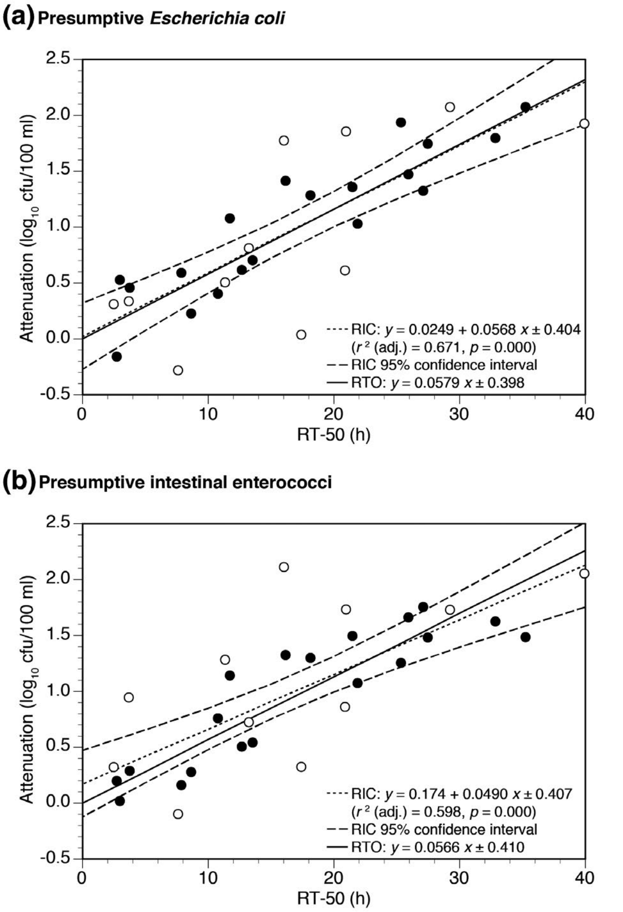

FIGURE 4 The statistically significant ($p > 0.05$) linear relationship between the cumulative log10 FIO attenuation recorded at the cell outlets and RT-50

TABLE 4 Summary of overall attenuation ($\log_{10}$) of faecal indicator organisms (FIOs) reported from other free water surface (FWS) constructed farms wetlands (CFWs) in the United Kingdom and Ireland[a,b]

	n[c]	Minimum	Lower quartile	Median	Upper quartile	Maximum
Escherichia coli[d]	20	0.000	1.191	1.757	2.693	4.505
Intestinal enterococci[d]	15	0.000	0.922	1.629	2.001	4.000

[a]Sources: Brettell et al. (2008); Carty et al. (2008); Gouriveaus et al. (2008); Harrington et al. (2007); Kay et al. (2005); Kay et al. (2010); Mustafa et al. (2009).

[b]In certain cases, attenuation rates have been calculated from other data reported or from further analysis of the raw data.

[c]n = total number of datasets included in the analysis.

[d]Either presumptive or confirmed enumerations.

4.2 | Guidance on CFW size requirement to meet FIO attenuation targets

RT is clearly an important design variable because the time taken for a pulse of polluted water to pass through a CFW will substantially affect the attenuation of FIOs and other agriculture-derived pollutants. RT-50 can be determined, as here, using a microbial tracer, and the results from Pwllpeiran have provided unique insight into the relationship between FIO attenuation and RT-50. Very similar rates of attenuation were recorded in both summer and winter, and combining the data from all seven sampling runs gave rates of pEC and pIE attenuation of 0.0579 and 0.0566 $\log_{10}$/h, respectively (Figure 4). On the basis of these figures, RT-50 s of 17.3, 34.5, 51.8 and 69.1 h would be required in order to give pEC attenuations of 1.0, 2.0, 3.0 and 4.0 $\log_{10}$ (equivalent to 90, 99, 99.9 and 99.99%), respectively. The corresponding figures for pIE are 17.7, 35.3, 53.0 and 70.7 h.

If it could be assumed that the water within a CFW is well-mixed and flow from inlet to outlet is not preferentially favoured or impeded, then the HRT could be estimated as the volume of storage unit/influent rate. Unfortunately, preferential flow lines will almost always develop and, once established, will likely be self-reinforcing. The fact that the HRTs estimated for the cell outlets at Pwllpeiran are *c*. three to five times greater than the measured RT-50 s indicates the extent to which preferential flow is occurring. Preferential flow therefore needs to be taken into account in designing CFWs to meet particular FIO attenuation targets.

Based on the maximum flows that a CFW is being designed to treat, then the relationships between the measured RT-50 and FIO attenuation established in the present study, in combination with an estimate of the likely ratio of HRT: RT-50, can be used to estimate the total area of the cell(s) with a water depth of 300 mm required to achieve a particular level of attenuation, as follows:

$$\text{Required CFW area}\ \left(\text{m}^2\right) = (\text{FYCA} \times \text{MWI} \times \text{HRT: RT} - 50 \times \text{RRT} - 50)\,/300\,\text{mm},$$

where FYCA = farmyard contributing area (m^2); MWI = maximum water input to be treated: rainfall and/or yard, parlour washings and so on (expressed as mm/h); HRT: RT-50 = estimated ratio (present study gives values from c. three to five times); and RRT-50 = required RRT-50 (h), based on targeted $\log_{10}$ attenuation and the figures reported above.

For example, for a contributing farmyard area of 5000 m^2; a peak water input of 10 mm/h; a target RRT-50 of 34.5 h (for 2.0 $\log_{10}$ or 99% attenuation of pEC); and an HRT:RT-50 of, say, 4, then the total area of the component cells of a 300-mm-deep CFW would need to be 23 000 m^2.

4.3 | Other design considerations

In the illustration above, the land requirement for the CFW is over four times that of the farmyard contributing area. This could be reduced substantially by, for example, routing relatively 'clean' run-off from roofs directly to land or a nearby watercourse—that is, effectively reducing the contributing area; and minimising preferential flow, by including frequent baffles, stabilised by vegetation—thereby reducing the HRT: RT-50 ratio.

Although fully vegetated systems will maximise the co-removal of BOD, COD, nutrients and SSs, reductions in the amount of UV light reaching the water surface as a result of the shade provided by emergent vegetation would appear to compromise their effectiveness in FIO attenuation. It is therefore recommended that at least parts of some of the cells are left unvegetated where FIO attenuation is a key consideration.

Carty et al. (2008, section 7.6) note that for a 'heavily loaded system the inclusion of an open water cell (0.5 m deep) at the initial stage of the CFW to act as a sediment trap may extend the operational life of subsequent cells before removal of material is required'. Although not explicitly investigated in the present study, such a cell would undoubtedly have additional benefits in terms of FIO attenuation: sedimentation of particle-attached FIOs and their retention in the accumulating bed sediments; absence of shade within the cell; and greater UV penetration in the generally less turbid water flowing through the remaining cells of the CFW. Periodically, the sediment fill could be cleaned out and disposed of to land—contributing organic matter and nutrients to the soil, while at the same time ensuring the rapid die-off of any residual FIOs.

4.4 | Monitoring and maintenance following construction

Experience at Pwllpeiran has demonstrated that even where a CFW has been professionally designed and constructed, leakages can occur. Vigilance therefore needs to be exercised during construction, particularly at sites where (as here) land drains are present. It is also recommended that water flow is monitored following construction to check that there is no significant leakage of water.

The present findings suggest that the development of preferential paths can considerably reduce the effectiveness of a CFW in attenuating FIO loads (and presumably other agriculture-derived pollutants). Although the incorporation of transverse baffles will inhibit this, these are likely to be eroded over time. It is important therefore that flow patterns within a CFW are monitored and remedial action taken to repair any damage—that is, the often held perception that these sustainable systems can be treated as 'fit and forget' installations is misguided and ongoing monitoring and maintenance, is essential.

5 | CONCLUSIONS

1. There is a very strong linear relationship between the mean RT-50 measured at each cell outlet and the cumulative upstream cell volume.

2. The RT-50 values are *c*. three to five times less than the calculated HRTs, which is presumed attributable to the development of preferential flow paths.
3. Despite the high concentrations of pEC and pIE in the 'slurry' injected during the experimental runs, the flow-weighted mean concentrations in the effluent from the CFW are low and unlikely to represent a significant microbial pollutant source at times of high flow.
4. Recorded pEC and pIE attenuations (ranges of 1.318–2.068 and 1.479–2.048 $\log_{10}$, respectively) in the experimental runs are similar to those reported from existing CFWs on livestock farms.
5. Attenuation rates in winter and summer are very similar, suggesting that in summer the increased shade afforded by the more substantial emergent vegetation cover compensates for the increased levels of UV light.
6. Attenuation of both pEC and pIE is strongly correlated with RT-50.
7. An equation is presented that enables estimates to be made of the area of wetland required to achieve a desired level of FIO attenuation.

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DATA AVAILABILITY STATEMENT

Data are available upon request from the authors.

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